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The Desert Research Institute (DRI) is developing strategies that integrate various data types to characterize groundwater resources for the identification of candidate well locations in central Ghana, West Africa. Study areas were selected over which remote sensing data of various scales were assembled along with all available hydrogeologic information. Water samples for chemical analysis were collected and numerous field observations were recorded during the survey of 200 wet and dry boreholes using Global Positioning System (GPS) receivers. All data collected were processed and integrated into a Geographic Information System (GIS). Relationships between features identified in remote sensing data, borehole records and other hydrogeologic characteristics are being examined to maximize water development efficiencies. The GIS modeling results are being tested with an ongoing drilling project. Preliminary results indicate a high correlation between drilling success and proximity to Landsat-derived lineaments.

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THE USE OF GIS AND REMOTE SENSING IN GROUNDWATER EXPLORATION FOR DEVELOPING COUNTRIES

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ABSTRACT

The Desert Research Institute (DRI) is developing strategies that integrate various data types to characterize groundwater resources for the identification of candidate well locations in central Ghana, West Africa. Study areas were selected over which remote sensing data of various scales were assembled along with all available hydrogeologic information. Water samples for chemical analysis were collected and numerous field observations were recorded during the survey of 200 wet and dry boreholes using Global Positioning System (GPS) receivers. All data collected were processed and integrated into a Geographic Information System (GIS). Relationships between features identified in remote sensing data, borehole records and other hydrogeologic characteristics are being examined to maximize water development efficiencies. The GIS modeling results are being tested with an ongoing drilling project. Preliminary results indicate a high correlation between drilling success and proximity to Landsat-derived lineaments.

1.0 INTRODUCTION

Lack of adequate potable and agricultural water supplies inhibits the progress of developing countries and is the cause of considerable hardship to humans worldwide. A thorough hydrogeologic understanding is often necessary for cost-effective water development. In many developing countries, remote sensing data often comprise the most accurate and comprehensive spatial information available. Establishing relationships between remote sensing data and hydrogeologic phenomena may maximize the efficiency of water development projects. The Desert Research Institute (DRI) is attempting to identify those strategies that effectively characterize groundwater resources in the country of Ghana using a Geographic Information System (GIS). For selected target areas, the strategies developed by DRI will recommend a combination of analytical methods, data types and data features which can be economically utilized to select well sites with the highest probability of success. While an emphasis will be placed on determining whether features mapped using remote sensing can be correlated with hydrogeologic phenomena, all methods and data types available will be tested in conjunction with the ongoing World Vision International (WVI) Ghana Rural Water Project (GRWP). This paper documents steps undertaken in constructing a GIS model for increased hydrogeologic understanding of study areas within Ghana, and presents preliminary results of the relationship observed between lineaments derived remote sensing and the location of wet and dry boreholes.

2.0 BACKGROUND

The West African country of Ghana experiences a lack of safe and adequate water for its inhabitants; 25 to 50 percent of the population do not have access to safe water supplies (Lean et al., 1990). Potable water shortages exist due to waterborne diseases and are exacerbated as sources desiccate during the dry season. A major objective of the Ghanaian government and non-government organizations (NGOs) is to improve the availability of safe and reliable water resources by drilling wells and installing hand pumps. However, throughout much of Ghana, including the study areas for this project, wet well success rates are below 60 percent. Wet wells for these hand pump installation programs are defined as having yields equal to or greater than 10 liters per minute. The major factor limiting success rates is the low primary permeability of crystalline and consolidated sedimentary rocks. Secondary fracturing in these rocks, however, may act to control the occurrence, movement and storage of groundwater. If fractures can be mapped and correlated with productive groundwater zones, well site selection may be improved.

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Fracture traces and ...ments have traditionally been mapped through remote sensing methods and have been differentiated based on ... Lattman (1958) defined fracture traces as natural linear features expressed continuously for less than one mi... ...le lineaments are greater than one mile in length. While fracture traces and lineaments have been shown to be barriers to groundwater flow (Taylor et al., 1992), most studies have correlated them with zones of increased fracture concentration, which can act as conduits for the transport and storage of groundwater (Lattman and Parizek, 1964; Parizek, 1976; Parizek et al. 1990). Previous studies by Boeckh (1992), Gustafsson (1993a) and Peter et al., (1988), have shown the utility of multiscale remote sensing strategies for increased hydrogeologic understanding in a variety of terrains and geological settings.

The integration of remote sensing data and GIS technology may provide a greater hydrogeologic understanding by combining physiographic, geologic, hydrogeologic and geochemical data in a spatially referenced model. GIS use in water resource evaluation has recently expanded with increasing emphasis in surface and subsurface applications (Maidment, 1991; Moore et al., 1991). Furthermore, the combination of remote sensing and GIS has shown promise for groundwater development in other regions of Africa (Gustafsson, 1993a).

STUDY AREA

A study area was developed to encompass two distinct geologic terrains within central Ghana (Figure 1). The Tease area lies entirely within the southern part of the Voltaian Sedimentary Basin, while the Nkawkaw area to the southwest straddles the contact between the Voltaian and the Precambrian basement rocks. These areas were selected due to the presence of an active drilling program with a large percentage of unsuccessful wells. Tease is located within the Afram Plains, a generally flat, low-lying region of the Voltaian Basin adjacent to Lake Volta, an 8500 km^2 lake formed by the damming of the Volta River in 1966.

The Voltaian Basin is a synclinal structure composed of relatively flat-lying Paleozoic sandstones, shales, and conglomerates that form outward-facing escarpments around the periphery of the basin (Kesse, 1985). Thin sections of quartz arenite sandstones taken near Tease and Fradaka in the Afram Plains indicate that clean uncemented sand has been compacted. Grain contacts are predominantly concave-convex indicating a high degree of compaction by deformation of ductile grains. Consolidation and cementation have reduced the rock volume, destroying much of the primary porosity and permeability. The stable mineral composition of the rocks permits little development of secondary permeability that might result from chemical weathering of intergranular cementing materials. The generally impervious nature of near-surface unweathered rocks minimizes direct infiltration, recharge and weathering, which are focused along joints and fracture systems. Groundwater flow in the basin has two primary components: a dominant vertical flow recharging fissures at depth and a more subdued subhorizontal flow parallel with stream gradients. The river systems, therefore, generally follow fractures where weathering and erosion have been enhanced and potential groundwater recharge is highest (Bannerman, 1988).

The southwest portion of the Nkawkaw area consists of metamorphic and granitic rocks of the Birimian System at the eastern edge of the Precambrian West African shield. The Birimian rocks have been folded, metamorphosed and in places assimilated by granitoid bodies. Folding is intense with dips commonly on the order of 30° to 90° along a northeast-southwest axis. Faulting and jointing is most commonly parallel and perpendicular to the strike of the folds (Kesse, 1985). As with the Voltaian, drilling data in the Birimian indicates discontinuous aquifers with primary storage located along fracture zones, lithologic contacts and horizons of weathered rock masses (Asomaning, 1993). A lithofeldspathic arenite from the Voltaian portion of the Nkawkaw area contains plagioclase, potassium feldspar, and metamorphic and sedimentary rock fragments that are normally unstable during the weathering processes, however, these fragments are unweathered in the sample, indicating a lack of diagenesis (Gin, 1994).

The rainfall pattern on the Afram Plains consists of a wet season, extending from March to October, followed by a four-month dry season. The annual average rainfall is approximately 140 centimeters. The natural vegetation of the Afram Plains consists of Guinea savanna. The major cover found in the Guinea savanna zone consists of a fire-controlled tree savanna community of broad-leafed deciduous trees densely distributed in a continuous cover of perennial bunch grasses and forbs (USAID, 1962). The Nkawkaw area normally receives more rainfall than the Afram Plains region, averaging 160 cm annually. The natural vegetation of the Nkawkaw area consists of thick deciduous forests within a semi-deciduous climatic region (Duah et al., 1993).

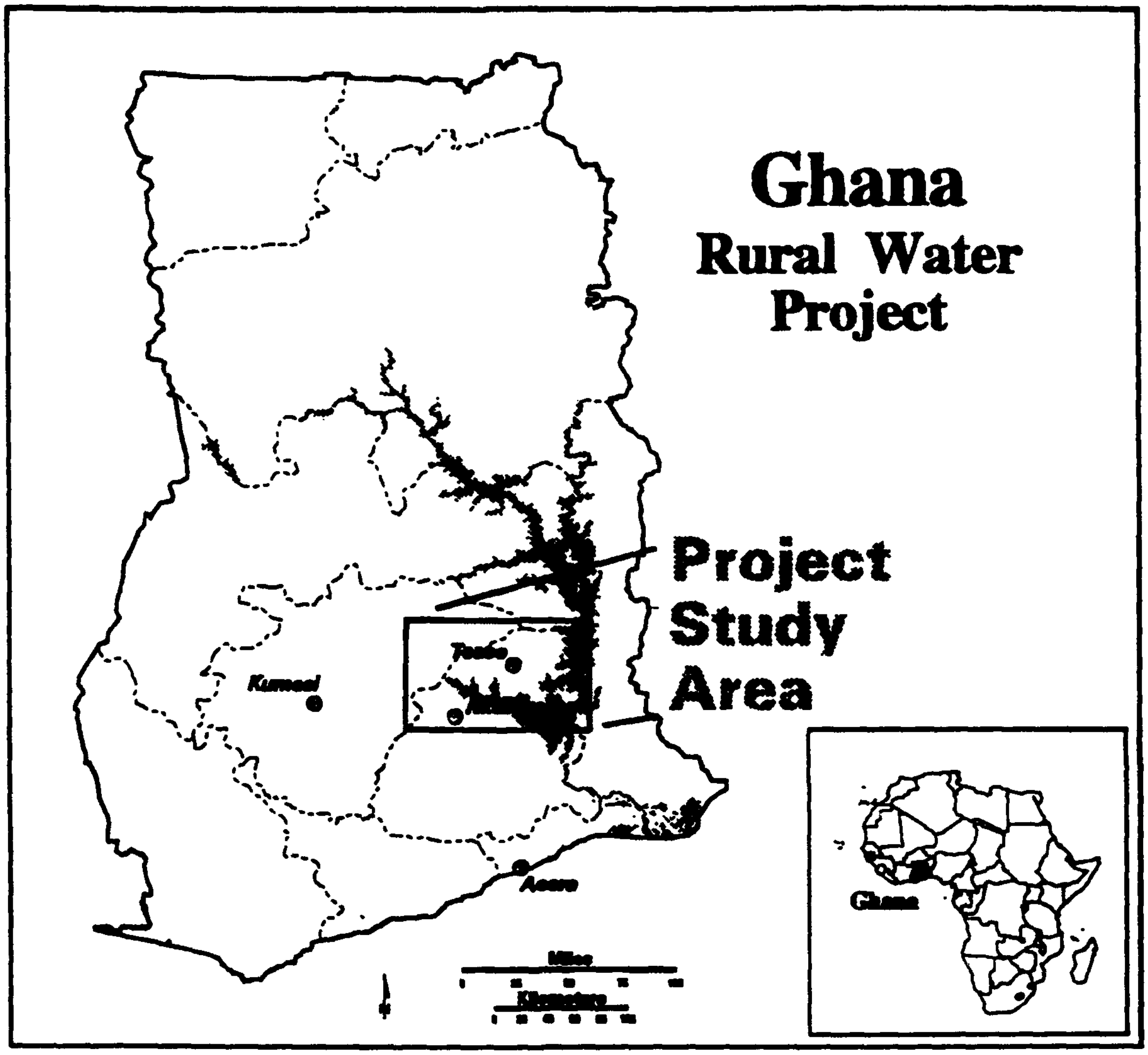

Figure 1. Project Study Area.

4.0 METHODS

Interpretation strategies are being developed that integrate ground-based and remotely sensed data in a GIS model. Critical steps in this development effort include: 1) the acquisition of all pertinent data; 2) data processing; and 3) database development. In evaluating the study area, potential sources and types of data necessary to form the GIS database were identified. Data were evaluated with respect to their potential usefulness, cost, and availability within project time constraints. Data types deemed necessary included: geologic, hydrogeologic, topographic, vegetation, and soil maps; aerial photography and satellite imagery; geophysical logs and surveys; borehole locations and related hydrologic information such as well yield, water level, water quality, aquifer test data (hydraulic conductivity, transmissivity, porosity, etc.); and reports addressing local and regional hydrogeologic investigations.

4.1 DATA ACQUISITION

Data collection efforts were generally divided among three types of information: 1) reports, maps and related data readily available from the United States and abroad; 2) data that would require collection within Ghana; and 3) remote sensing data. General background information through water exploration program reports specific to our study area were collected through standard literature search methods and various mapping agencies. Similar searches were conducted for resources which discussed the use of aerial photography and other remote sensing methods for investigating geologic and hydrologic phenomena with an emphasis on fracture trace and lineament analysis. Many of the resources collected referenced other work and reports only available within Ghana.

4.1.1 Data Collected in Ghana

A trip was made early in the project to gather information identified through literature searches and other sources, to identify new information sources pertinent to the project, and to arrange for future data transfer with WVI and other agencies. Copies of topographic and geologic maps were obtained along with reports and any available well logs. The release of data inside and outside Ghana often required appropriate agency permission.

A second field trip was necessary to accurately survey a significant number of boreholes for the GIS to determine and test relationships between identified features and borehole characteristics. Three factors created large uncertainties in borehole locations: 1) borehole locations on drill logs were identified only with respect to the communities to be served; 2) some boreholes were located as far as 2 km from their associated village; and 3) many communities postdated the topographic maps. These factors, combined with cost constraints and accuracy requirements, dictated the use of sub-20 m Global Positioning System (GPS) receivers to accurately survey borehole positions. Logistical consideration suggested using two teams, each with a GPS receiver in stand-alone mode to survey the maximum number of well sites possible. To circumvent the single-mode, 100-m limitation imposed by selective availability (SA), arrangements were made through the U.S. Army Corps of Engineers to use two Magnavox MX 7100 receivers with the PPS code enabling 10 to 20 m accuracies.

While borehole locations were the primary objective of the second in-country visit, numerous other data observations were recorded during the well site surveys. These data included elevation, water level, soil type, surficial geology, topographic setting, hydrologic indicators and classification of surrounding vegetation and land use at 50 and 500 m. Sketch maps, operating status and water samples for gross chemistry and isotopic analysis were collected along with temperature, EC and pH. Whenever possible, site selection criteria were obtained from the Ghanaian hydrogeologist responsible for siting wells. Well positions were also plotted on Landsat imagery and aerial photographs using scale positioning software available on Trimble's Scout GPS receiver. Because borehole elevations and water level data were necessary for constructing accurate potentiometric maps, additional steps were taken to improve elevation measurements. As GPS-determined altitudes are generally limited to 1.5 times the horizontal accuracy (15 to 30 m), elevations were determined by plotting their horizontal positions on 50-ft contour maps. Improving this further, relative well altitudes were recorded with barometric altimeters in the field using time and base station barometric corrections.

4.1.2 Image Data Acquisition

Initial data searches revealed a limited availability of usable Landsat Thematic Mapper (TM) and SPOT data due to cloud cover during the extended wet season and attenuation by clouds, haze, dust, and smoke during the dry season. Quality concerns and time constraints dictated that two TM scenes be acquired during the dry season, only after viewing the actual data sets. Due to a lack of available archived SPOT panchromatic data, a Special Acquisition Request (SAR) was made in January 1993 for the collection of 11 panchromatic SPOT scenes. Of 16 SPOT scenes acquired since the request, none have been acceptable for analysis over the study areas due to atmospheric conditions and sensor adjustments. Given the difficult atmospheric conditions and vegetation cover, attempts were made to acquire ERS-1, Seasat and Shuttle Imaging Radar data, but were unsuccessful. Digitally scanned data sets of declassified Russian MK-4 photography at 7.5 m resolution were identified in an archive in Moscow, but closer examination found the data to be corrupt. Data from the KVA-1000 camera system for the Afram Plains were not available and could not be acquired within project time constraints. 1972-73 black and white infrared stereo photography of the study sites at 1:40,000 scale was collected only after obtaining permission from the Ghana Survey Department. In addition to the 1:40,000 frames, 1:10,000 enlargements of selected areas were also acquired.

4.2 DATA PROCESSING AND INTERPRETATION

4.2.1 GPS Data Processing

The ease and functionality of GPS have allowed the opportunity to mix data from different coordinate systems and datums within a GIS. While coordinates are the thread that tie all data together, many GISs have limited coordinate system and datum transformation routines. Thus, it is critical that coordinates be transferred to the same coordinate system and datum before insertion into any GIS. GPS–determined coordinates taken with respect to the WGS84 datum were converted into the "Accra datum" using the "Geographic Calculator" to minimize database inaccuracies. Coordinates were transformed using the Molodensky Method which shifted positions by up to 350 m. Bearing and distance measurements were used to determine GPS offset locations with the National Geodetic Survey (NGS) INVFWD program.

4.2.2 Image Processing–Landsat TM Data

Level 0 Landsat TM data were precision–corrected using a cubic convolution resampling method and 1:50,000 scale topographic maps. The Root Mean Square (RMS) error of the georectification process was one pixel or 30 m. Two adjacent Landsat scenes (Path/Row 193/055 and 194/055) were digitally mosaicked using ER Mapper image processing software. Various color composites were generated to determine the best band combinations for analysis of lineaments, fracture traces and vegetation anomalies. The Landsat data contained bad scan lines which, with the added attenuation contributed by smoke and dust in the atmosphere, prevented the effective use of TM bands 1 and 2 in the construction of composites. Therefore, band combinations 453 and 743 in RGB were used to interpret the imagery. Each color composite was edge–enhanced using a 3x3 edge sharpening filter. In addition to generating edge–enhanced color composites, directionally filtered images were constructed using TM band 4 in a multi–step procedure similar to that described by Moore and Waltz (1983). The resultant directionally enhanced component images represented four azimuth bearings: East–West; North–South; Northwest–Southeast; Northeast–Southwest. Principal Component (PC) transformations were performed on bands 543, 743 and 745 to produce three–band PC composites in RGB. In addition, PC1 from bands 743 and 543 were used as greyscale images.

4.2.3 Image Interpretation–Landsat Data

The general interpretation approach has been to digitize linear features on screen using the annotation tool in ER Mapper. Interpolation and extrapolation of features have been avoided to produce a more "objective" lineament map, for subsequent tectonic interpretation. Lineament interpretation can be carried out in different ways depending upon the image types available, ground truthing required, and aim of the interpretation. If the aim of the interpretation is to reproduce the general fracture trends of the area, the positional accuracy of the lineaments is not as important as the orientation and correct frequency in each interval. If, on the other hand, the position of the inferred fracture zone is to be used in comparisons with other spatial data such as boreholes, the positional accuracy is more important. Shuman (1991), determined that lineament frequency decreases as lineament size increases, while a plot of average lineament length against imagery scale shows a positive polynomial relationship. The higher spectral resolution of TM verses SPOT data is more important for lineament analysis in areas of dense vegetation. Therefore, both spatial and spectral image resolution has a great impact on image interpretation results.

In this study, a systematic mapping effort was conducted to perform the lineament and fracture trace analysis based on techniques adapted from Wheeler and Wise (1983). This effort had several objectives: 1) consistently identify lineament and fracture trace features; 2) classify the lineaments based on a rating system related to vector length, orientation, and feature prominence; and 3) eliminate non–structural and "false" lineaments. The interpretations were performed with no prior knowledge of wet or dry well locations.

The Tease area Landsat scene was subsectioned into overlapping 1:100,000 scale images on the workstation screen. The study areas were covered using 50 percent overlapping windows to avoid overlooking features at window edges (Gustafsson, 1993b and 1994). The strategy employed evaluated three sets of image data: color composites, directionally filtered images, and principal component composites. Three operators independently mapped all lineaments. Individual interpretation results were digitally combined using different colored vectors to evaluate mapping results, compare class types, and eliminate "false" lineaments. The Nkawkaw area interpretation was carried out at a larger scale than in the Tease area, due to the high density of lineaments adjacent to the Voltaian escarpment. The interpretation scale on screen was approximately 1:45,000, enabling more accurate positioning of linear features.

4.2.4 Photo Interpretation

The aerial photography was interpreted stereoscopically on 1:40,000 scale prints with 2x and 10x magnification to enable better positioning of small or narrow linear features. The aerial photos were analyzed by several interpreters, focusing on photo linears within a 2-km radius of existing wells and villages. This constraint was implemented because 2 km was the maximum distance a well would be placed from a village by WVI. The interpretations were performed using acetate overlays and the identified photo linears were classified into three categories according to their prominence. Upon completion of the independent analyses, the mapping results were compared, "false" fracture traces were eliminated, and features checked for redundancy.

4.3 DATABASE DEVELOPMENT

The GIS database continues to be developed using Arc/INFO software. To date, base map, well location, topographic, field observation, and satellite remote sensing data have been fully automated and integrated into the GIS (Figure 2). GIS display and georelational capabilities allow for efficient analysis of both raster and vector data types. All integrated data will be managed within a coherent spatial reference frame for development of strategies to identify data types and analysis techniques most useful for siting well locations.

4.3.1 Base Maps

The project study areas were subdivided for reference into a series of 15-minute quadrangles. Corner tics of these quadrangles serve as registration control points for all base map automation. The GIS uses a Universal Transverse Mercator (UTM) coordinate system and is based on the 1:50,000 scale topographic map series produced by the Ghana Survey Department.

The 1:50,000 map series provides essential base map data, including surface hydrography, transportation features, and village locations. Surface hydrographic features are valuable for understanding groundwater flow, while village locations and transportation features are important from a well-siting perspective. The source maps were available on paper media only, thus map registration errors were corrected to account for map shrinkage. Data layers in the GIS were appropriately coded with as many descriptive attributes as could be derived from the base maps. Drainage features were coded as perennial or ephemeral; transportation features were coded to reflect level of use and seasonal reliability; and communities were coded to capture variations in spelling.

4.3.2 Well Locations

Understanding the spatial distribution of existing wells is clearly an important first step in developing a well-siting strategy; a preliminary screening of productive versus 'dry' wells can provide a valuable initial assessment of groundwater conditions. Furthermore, accurate locational (and elevation) data for these wells are critical for maximizing use of borehole information collected during drilling. Prior to the GPS survey, a preliminary well location data layer was developed, using the spatial tools of the GIS to place the wells within the village to which they were referenced. The preliminary well location data layer gave project hydrologists a provisional set of data from which to develop early working hypotheses. Upon completion of the GPS survey, all borehole positions in the GIS were updated to reflect their new positions.

4.3.3 Well Logs

Hydrogeologic data in the form of drafted borehole logs are generated as part of WVI's ongoing water well drilling program. Borehole logs include hydrogeologic and lithologic descriptions of rock units encountered during

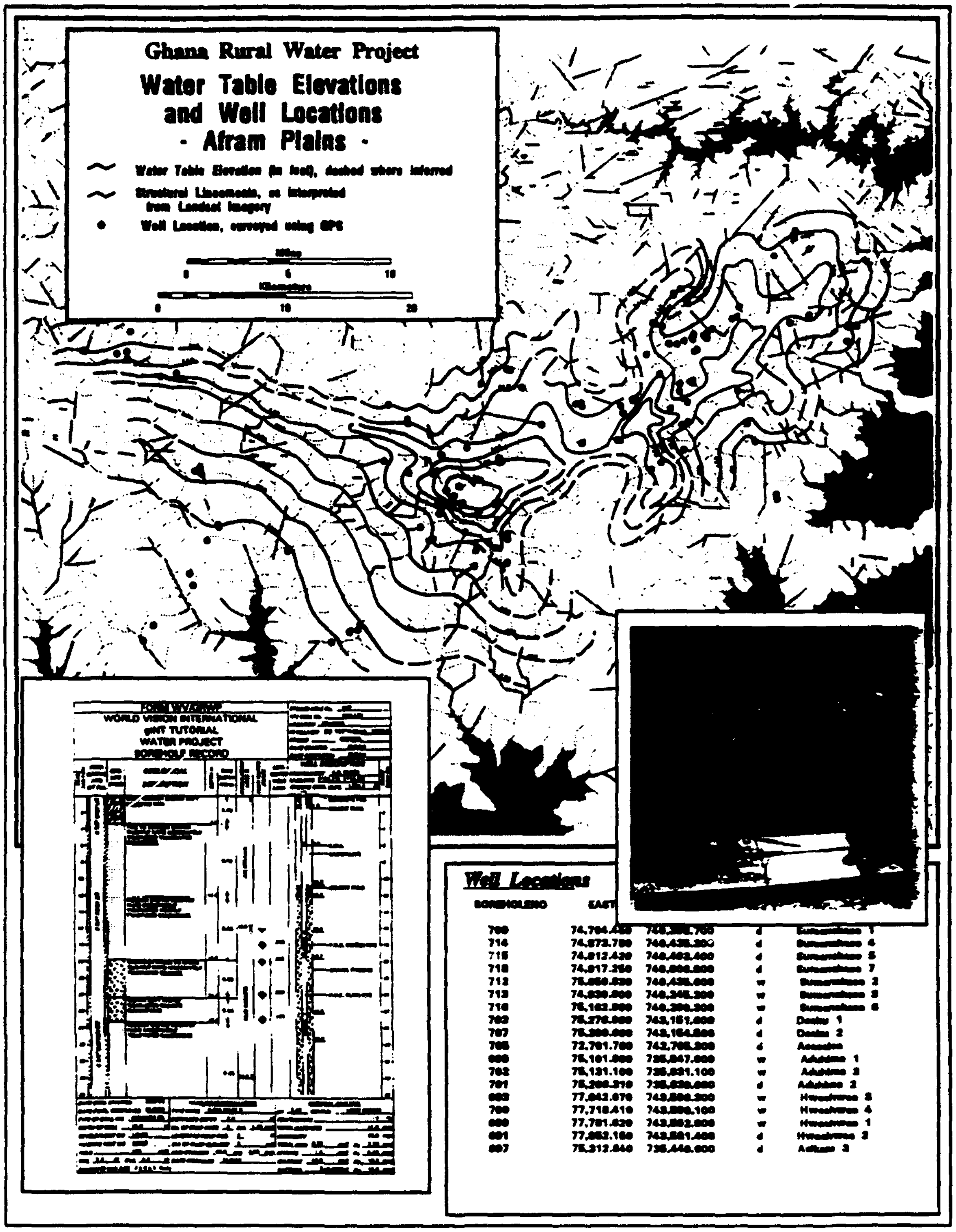

Figure 2. GIS Integration of Various Data Types.

drilling, well construction information describing casing and screen intervals, and development history of the well. In addition, the logs contained water chemistry and well yield information, vital to the characterization of groundwater flow in the study areas. Data entry templates were created for efficient entry of large quantities of well log information. In all, 14 separate well log data files were created, each containing from eight to 40 descriptive attributes. To expedite this process for future boreholes, WVI has been provided with logging software, so that subsequent well logs can be created and transferred digitally. In the GIS, all well log files are linked relationally to the well location attribute table, so that any combination of well construction, lithologic, geochemical, or hydrogeologic characteristics, from any number of wells, can be viewed in spatial context with one another.

4.3.4 Topography

Topographic data are a vital in determining water table elevations and, subsequently, developing potentiometric maps. As no digital topographic data of sufficient resolution were available, paper copies obtained in Ghana were scanned to produce a Digital Elevation Model (DEM) and contour plot files. These data will allow three-dimensional viewing, watershed calculations, and tectonic interpretation, and permit refinement of well elevations and potentiometric maps.

4.3.5 Remote Sensing Data Integration

The lineaments and fracture traces identified in the digital analysis of Landsat TM data were automated and incorporated into the GIS. The Landsat-derived lineaments and fracture traces were imported as vectors from ER Mapper. As a data layer in the GIS, these features were classified based on length and orientation and assessed for their proximity to existing wells. The fracture traces derived from stereoscopic analysis of 1:40,000 scale black-and-white aerial photography will be digitized after being transferred to rectified 1:40,000 scale photomosaics. Once integrated into the GIS, spatial analyses will be conducted, assessing fracture trace properties relative to existing wells and their hydrogeologic characteristics.

5.0 RESULTS AND DISCUSSION

5.1 DATA COLLECTION

Initial literature searches and an early reconnaissance trip to Ghana provided the means to collect most existing data over the study area. Project emphasis on fracture trace analysis, coupled with previous studies having shown the relatively narrow nature of fracture zones (Parizek et al., 1990), required the collection of more accurate well positions. The resulting GPS field effort surveyed over 200 boreholes in 82 different communities. Numerous other field observations were simultaneously collected in addition to water samples from 50 sites. Gross chemistry and isotopic analysis is underway, while all other data have been entered into the GIS.

5.2 REMOTE SENSING DATA

Image analysis results of the Landsat data indicated that the most useful band combination for discriminating lineaments in the Tease area was the PC composite from TM bands 543. While the 453 and 473 color composites provided some utility, the PC composite better discriminated soil brightness and vegetation differences, with reduced noise levels. The directionally filtered images contained too many image artifacts to be of use in this study. This was due in part to the banding effects in the Landsat imagery as well as the relatively flat terrain and uniform land cover of the study area. Most of the lineaments are related to structurally controlled drainages in valley bottoms. Analysis of the predominant lineament orientation indicated a maxima between 270–275°, with a less dominant orientation found between 330–335° (Figure 3). A total of 900 lineaments were identified in the Tease area. The lineament lengths varied between 84 and 5938 m with a mean length of 1377 m. The orientations are consistent with regional structural processes and fractures observed in the field. The dry season acquisition dates of the Landsat imagery permitted the effective use of riparian and tap root vegetation species as indicators of fracture systems. In some cases, riparian species in drainage basins helped accentuate lineaments.

The most useful Landsat band combinations for lineament interpretations in the Nkawkaw area were the PC composite from TM bands 543 and PC1 from bands 743 in greyscale. The interpretation resulted in 1037 lineaments

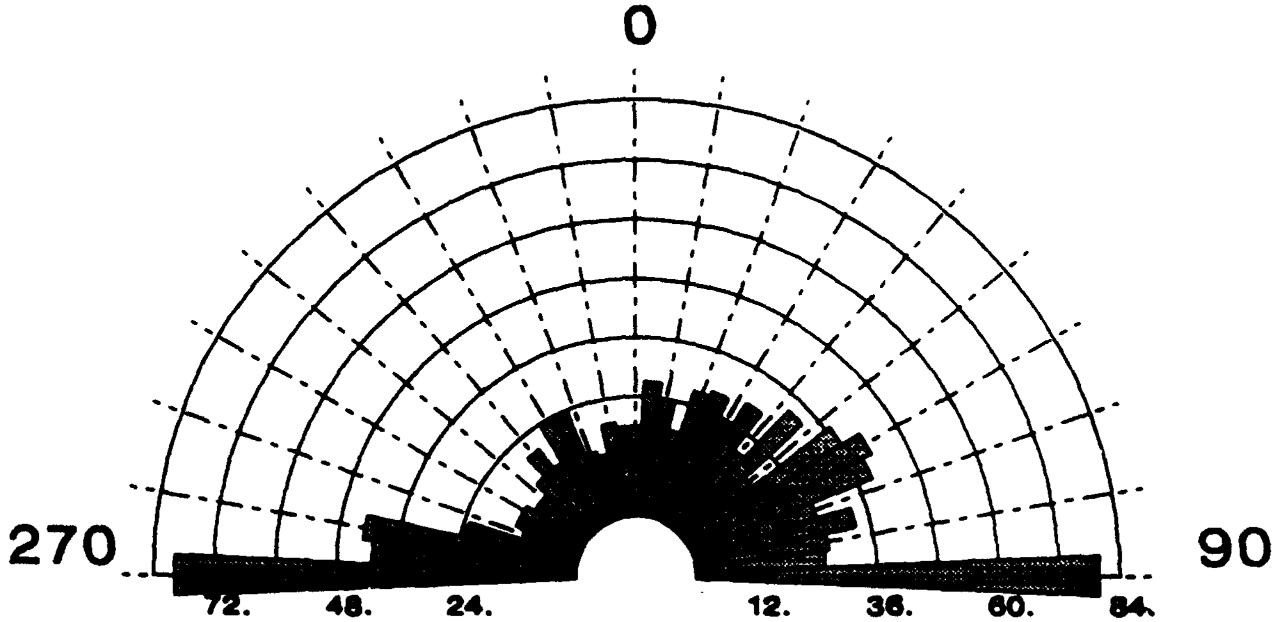

Figure 3. Frequency and Orientation of Fracture Traces and Lineaments in the Tease Area.

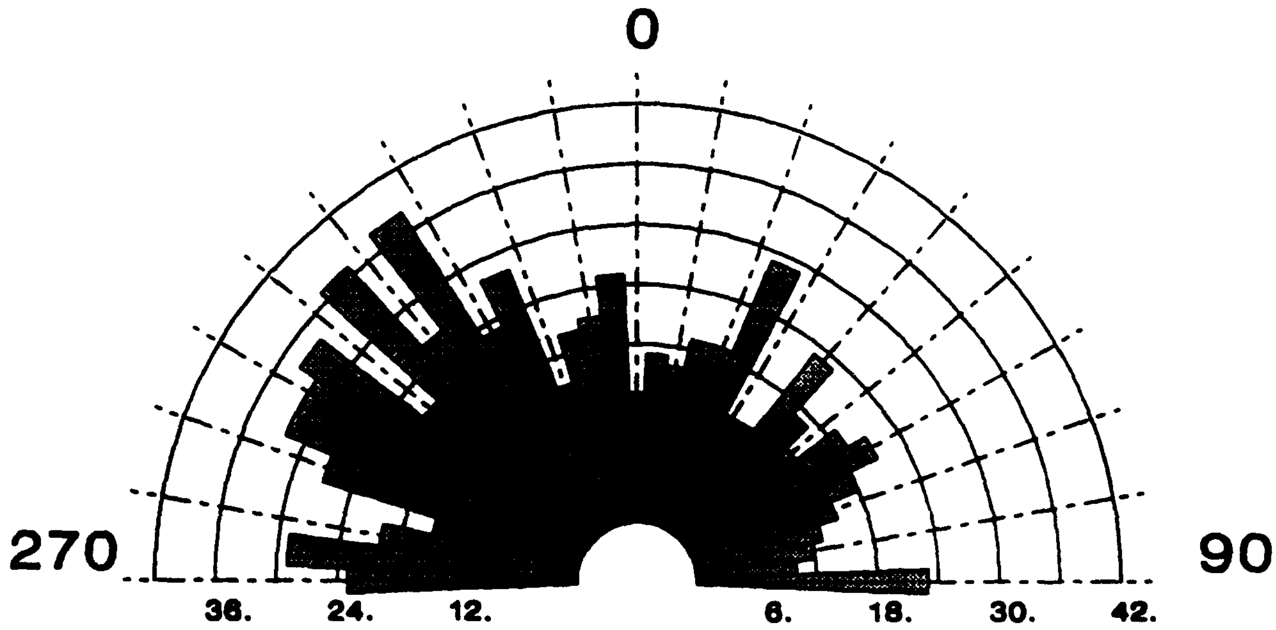

Figure 4. Frequency and Orientation of Fracture Traces and Lineaments in the Nkawkaw Area.

identified in the Nkawkaw area, with the majority of lineaments found in a 10-km-wide section along the northwest-southeast-trending escarpment. The lineament lengths varied from around 100 m to 10 km with an average around 1200 m. The predominant lineament orientations indicate maximas at 325°, 315° and 305°, with less dominant orientations found between 290-300° (Figure 4).

Although photograph contrast is poor (due primarily to atmospheric haze), preliminary results of air photo interpretations indicate that, the larger scale and stereoscopic characteristics allow the discrimination of fracture traces not discernible on the satellite imagery. Subtle fracture traces linked to changes in tree heights and soil tonal alignments were identified. In several cases, fracture trace intersections were found near villages, providing new potential targets for future drilling programs. Once integrated into the GIS model, spatial analysis operations can be conducted to determine relationships between photo-derived fracture traces and other features in the database.

5.3 GIS MODELING RESULTS

While GIS modeling efforts are only preliminary, initial proximity analysis of fracture traces and lineaments derived from Landsat TM imagery and borehole locations indicates promising results. Almost 95 percent of all wells surveyed in the Tease area are located within 2 km of identified fracture traces and lineaments. This suggests the availability of potential targets within the present project drilling constraints. Of greater significance, 100 percent of all wells within 100 m of identified fracture traces and lineaments are wet, with a decrease in wet well percentage as the distance from a fracture increases (Figure 5). Furthermore, less than seven percent of wells within 250 m were dry. These initial results indicate that 30-m Landsat TM data may be an effective tool for siting wells. These findings also support previous observations (Bannerman, 1988) that fracture zones in the area act as primary pathways for storage and movement of groundwater. Further analysis of fracture orientation and length, proximity to well location, fracture/well yield relationships, and lithology will be conducted in hopes of determining other factors critical for improving drilling success rates and well yield.

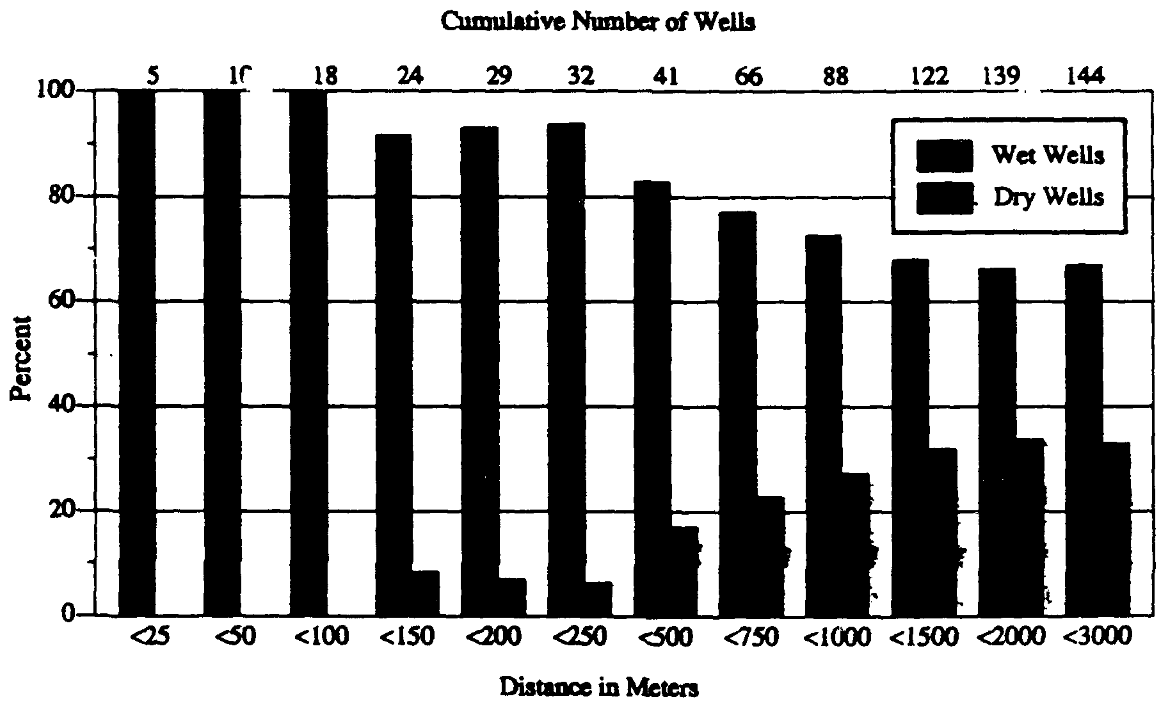

Figure 5. Distribution of Wet and Dry Wells vs. Distance from Nearest Lineament or Fracture Trace.

6.0 SUMMARY AND CONCLUSIONS

Preliminary results indicate that satellite imagery, when integrated with other hydrogeologic data, may be a valuable tool in GIS-based determination of potential well targets. The synoptic view provided by satellite imagery allowed a better understanding of the regional hydrogeologic settings in this project. The full potential of remotely sensed data, however, has not been realized due to the limited availability of other types of imagery over the study areas. The lack of SPOT data and Russian satellite-based imagery, as well as the absence of radar coverage, has inhibited the application of additional remote sensing techniques for the evaluation of hydrogeologic features in the study area. Efforts to acquire image data, specifically SPOT panchromatic scenes, shall continue through the end of the 1994 dry season in hopes of improving the hydrogeologic GIS model. The stereoscopic, high resolution aerial photographs, though poor in quality, allowed the identification of subtle fracture traces not discernable on the Landsat data. If similar relationships are found between photo-derived linears and borehole success, it may provide new drilling targets closer to the communities in need.

GIS database development and data integration in a developing nation present a variety of unique challenges. Uncertainty regarding the availability and format of numerous data resulted in many delays in database development activities. Remote site data collection efforts require thorough logistical considerations, contingency plans, and spare equipment, especially in areas environmentally hostile to modern data collection instruments. It is critical that the GIS operator be completely aware of the geo-referencing systems, datums, and elevation surfaces associated with the various data types collected, so as not to mix incompatible coordinates.

Although the results of this paper and the project are preliminary, several significant relationships between features derived from the Landsat TM data and hydrogeologic characteristics of the Tease area were observed. Additional proximity analysis, integration and analysis of fracture traces derived from the aerial photography, and correlation of well yields to lineament length, orientation and geology, will be conducted as the project progresses, the ultimate goal being the selection of well sites with the highest probability of success in different geologic settings.

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